Droplet-based High Brightness LPP Light Sources for High Volume Metrology and Inspection Applications

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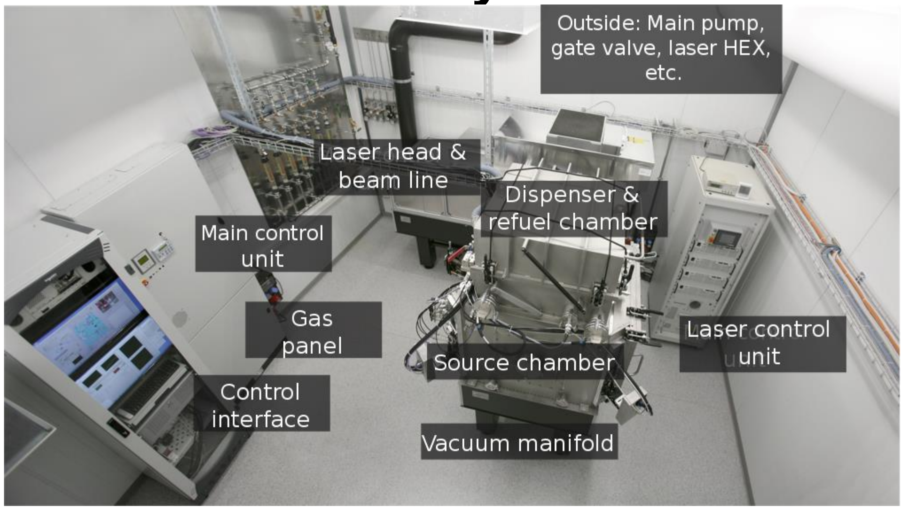
Presentation Outline

- ALPS Program Overview
- Plasma EUV Emission Studies
- VUV Emission
- Plasma Debris Studies
  - Ion debris studies
  - Droplet fragment debris studies
- Debris Mitigation Strategy
- Life-time Assessment of Collection Optics
- Summary & Conclusions

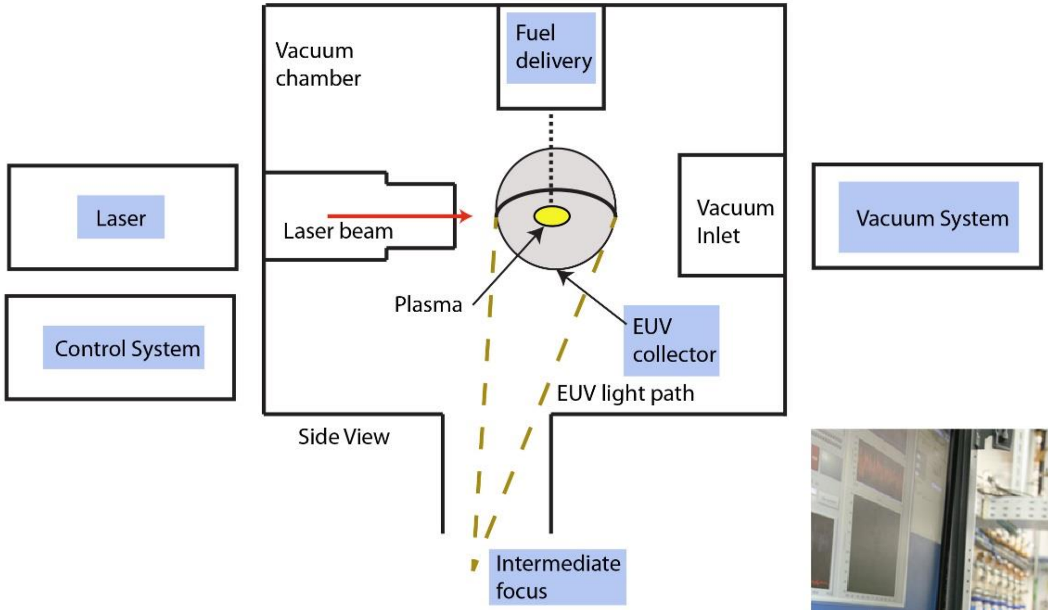
10 Years of LPP EUV Light Source Development – ALPS II Key Numbers

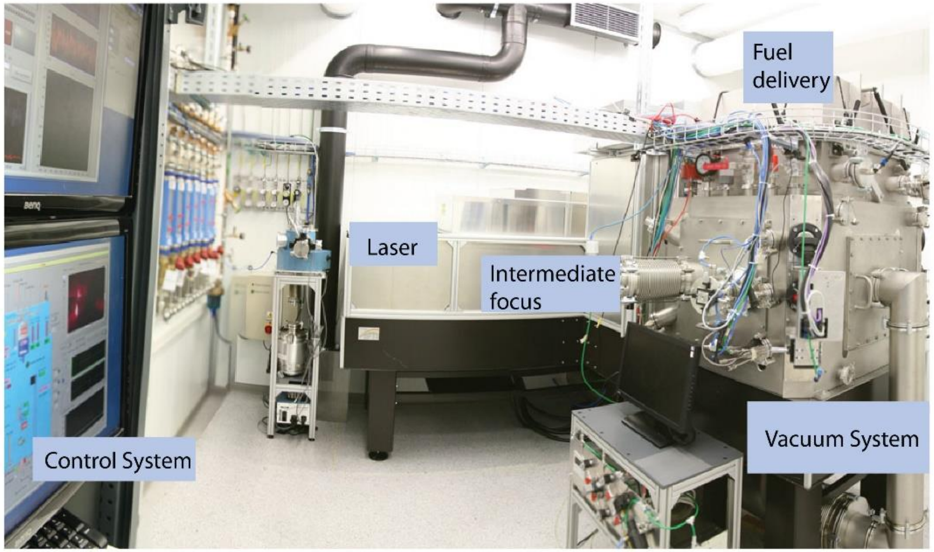


Parameters	Value
Laser power on target (W)	1300
Laser frequency (kHz)	>6
Laser focal spot - FWHM (µm)	70
Conversion efficiency (%)	>1%
Source power at the source (W)	>12
Source brightness (W/mm^2sr)	350

- Nd:YAG laser: average power of 1.6 kW, λ = 1.064 µm, 6-20 kHz rep. rate, typically I = 200 GW/cm^2
- 6th generation in-house droplet dispenser with >30 µm tin droplet generation for hours of operation.
- Closed loop droplet tracking system with laser triggering on individual droplets enables droplet-laser alignment within <10% of droplet diameter.
- Full diagnostic including in-band energy monitors and out-of-band spectroscopy
- Debris mitigated grazing incidence collector, including clean IF module with imaging capability.
- Compatible with various collector configurations

ALPS II Prototype Laser-produced Plasma Source for metrology and inspection applications during HVM

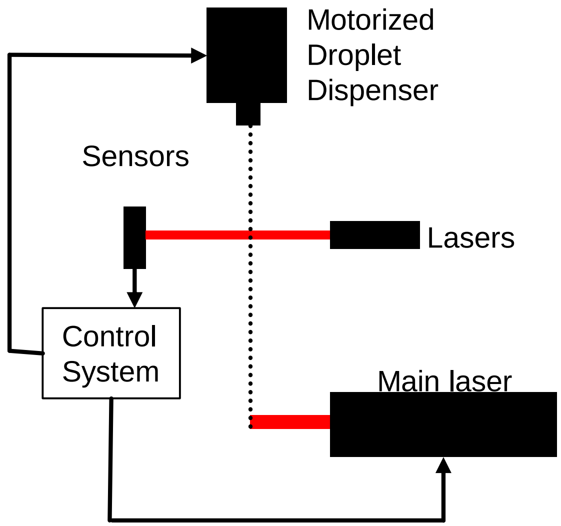


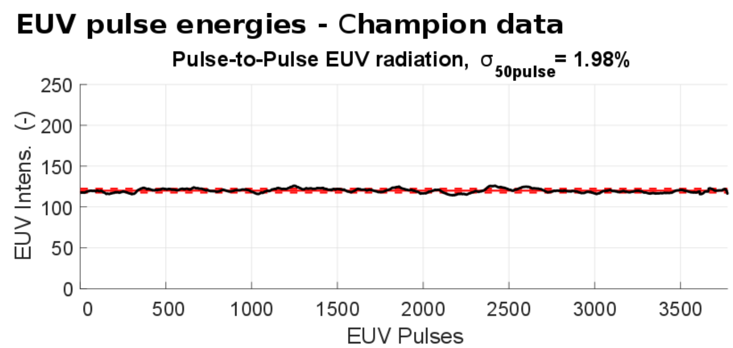


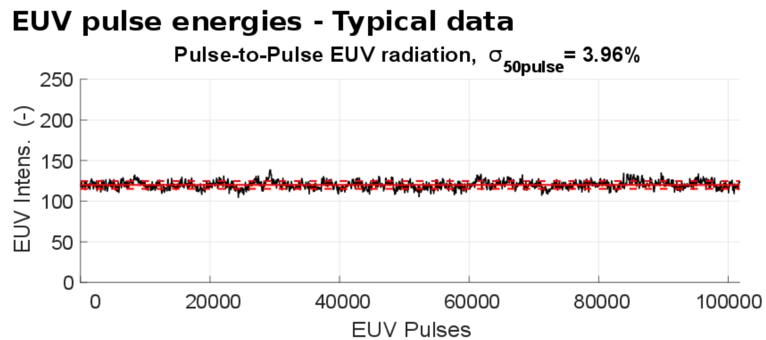
www.lec.ethz.ch/plasma

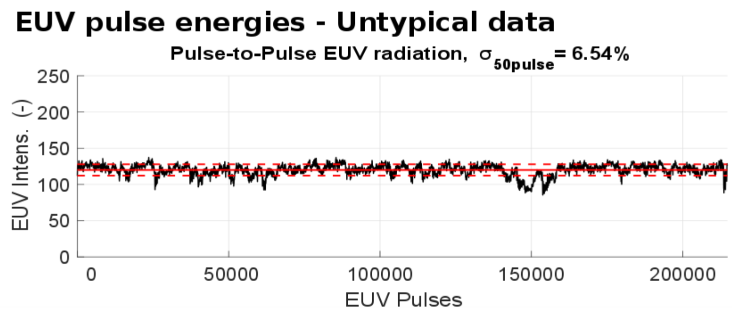
EUV Emission Stability

- EUV energy monitor (ML, Zr filter) and gated hardware integrator. Source operated at 7 kHz repetition rate.





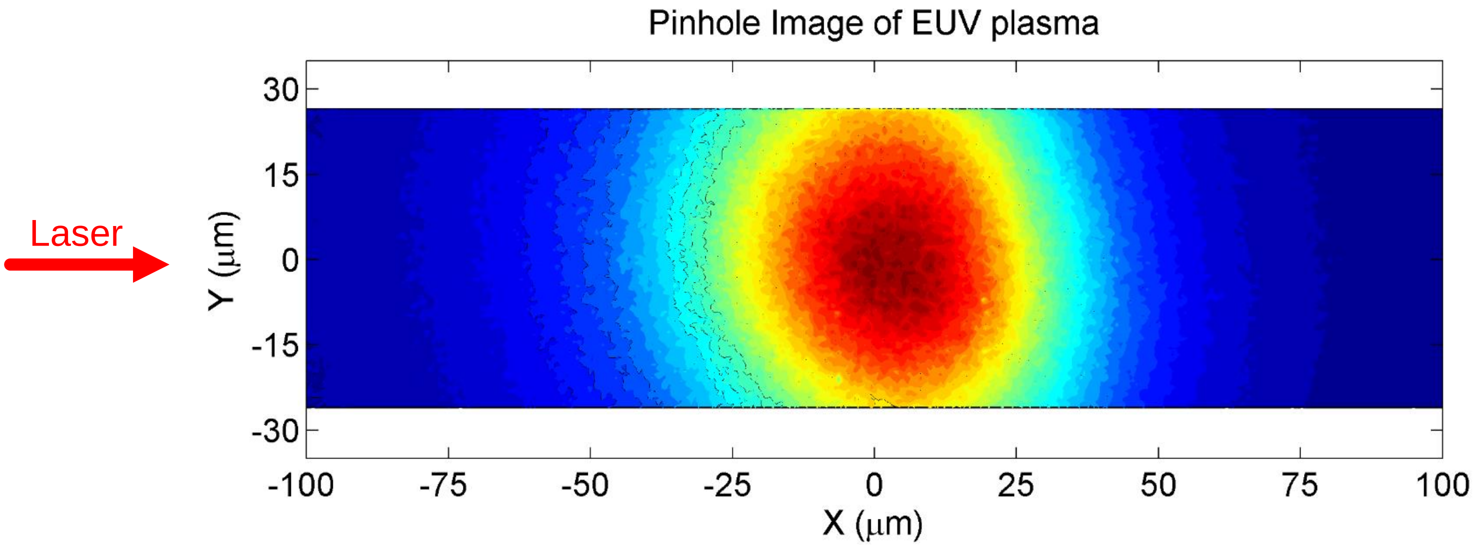




- **Pulse-to-pulse stability of EUV energy of 1.98% ($\sigma_{50pulse}$)** has been achieved.
- Strong dependence between EUV pulse-to-pulse stability and trigger / droplet tracking performance

EUV Source Size from Pinhole Camera Measurements

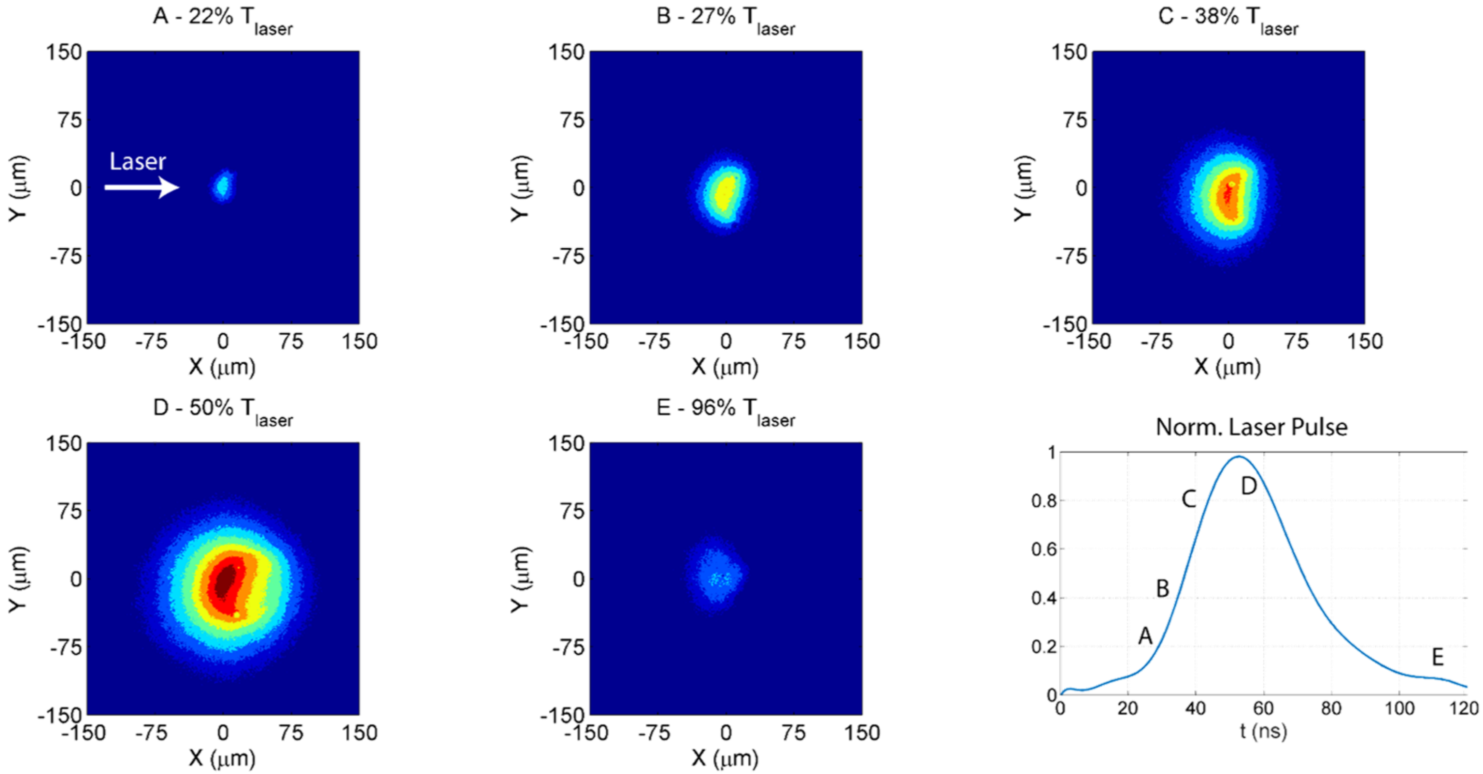
- EUV emission (Zr-filtered) recorded with an X-ray CCD pinhole camera, located at 20 mm from the plasma with an orifice size of 20 µm (magnification 40x).
- Exposure time of 140 ms for standard operating conditions (tin droplets, 200 GW/cm^2, camera at 90° from laser axis)



- The dimensions of the plasma in the direction of the laser axis and the direction of the train equal 60 µm and 70 µm (FWHM), respectively.
- For a given etendue requirement, the source dimensions determine the collection angle, hence size of the source mirror.

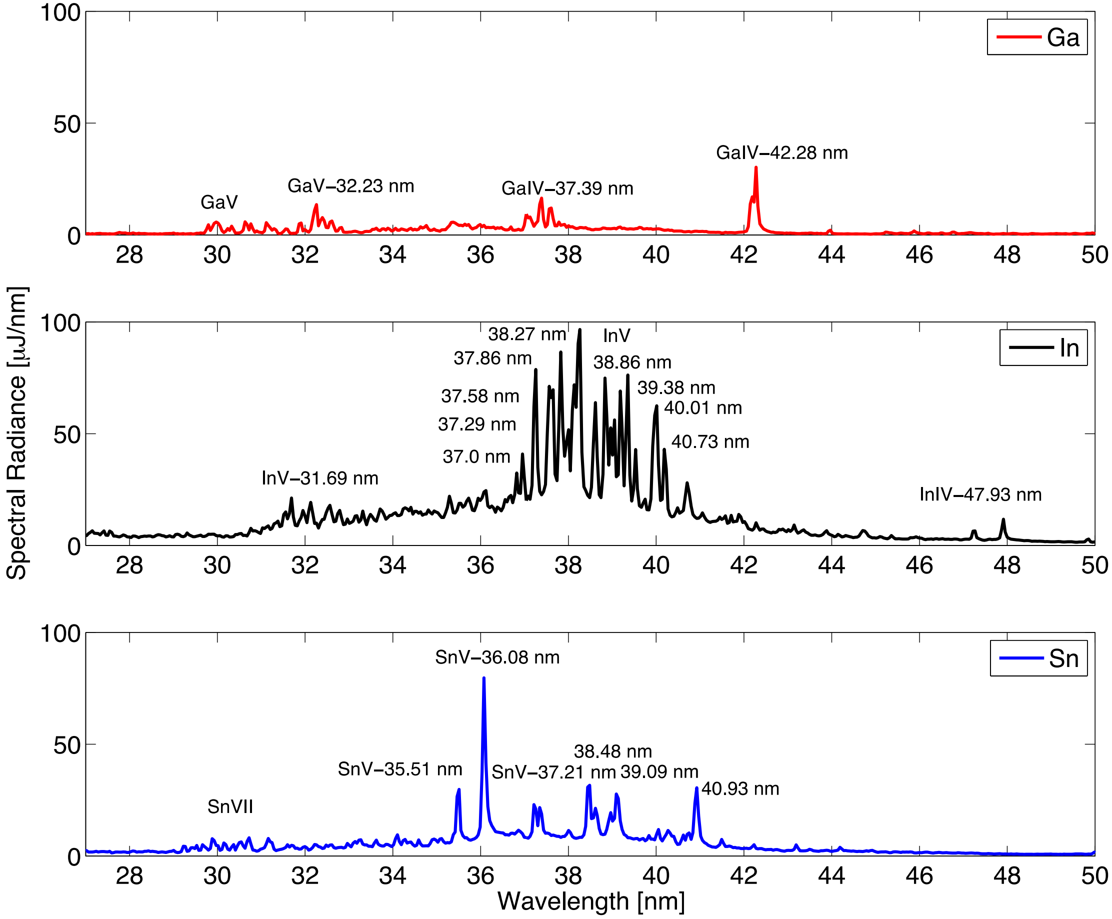
Fast Nanosecond Imaging of Plasma (Visible)

- Visible (400 – 700 nm) emission captured from a single plasma with an exposure time of 5 ns for standard operating conditions (tin droplets, 200 GW/cm^2, camera at 90° from laser axis)
- Resolution of single pulse dynamics (not captured by long exposure of pinhole camera)



- Peak emission obtained around peak laser intensity
- Emission is mainly Bremsstrahlung emission, as opposed to line emission from Sn and Sn^+, which appears at larger time scales.

VUV Emission in the Spectral Range from 30 to 50 nm



- Charge states from 3+ to 6+ observed from 30 to 50 nm
- Indium has higher spectral radiance in He with respect to Sn and Ga

Integrated Power (Watt)

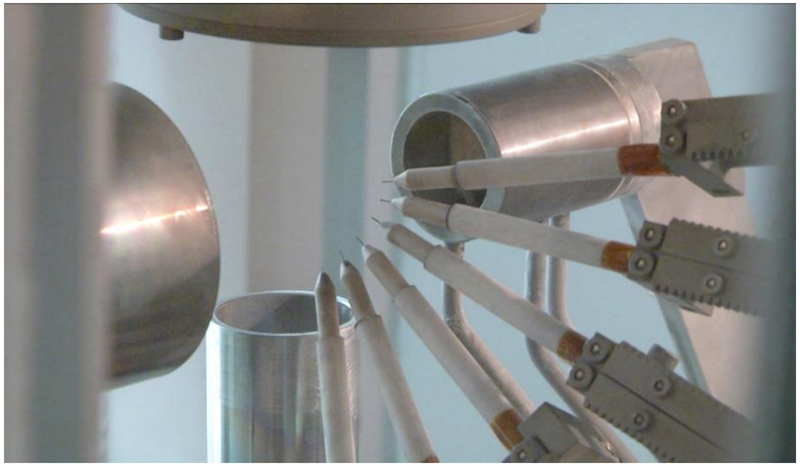
Range (nm)	Ga	In	Sn
30-50	**0.27**	**1.70**	**0.69**
117-137	**0.94**	**1.66**	**1.34**
30-163	**2.38**	**5.8**	**3.7**

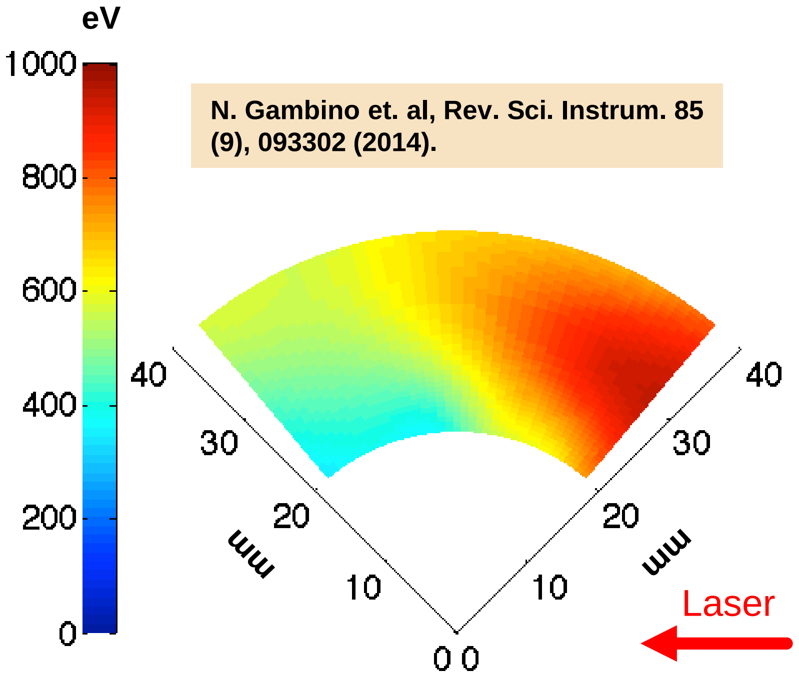
- Source power in the range of watts for sub 160 nm

N. Gambino et. al, Spectrochimica Acta Part B (2016)

Two-dimensional ion mapping measured by Langmuir Probes

- Temporally and spatially resolved ion and electron distribution to yield a hemispherical mapping around the droplet.
- Kinetic energies are derived from time-of-flight measurements



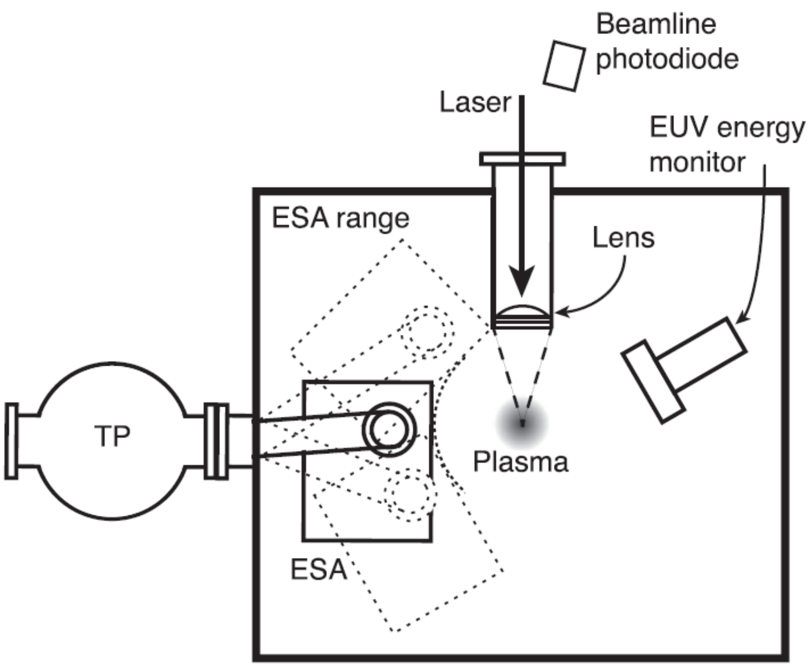


N. Gambino et. al, Rev. Sci. Instrum. 85 (9), 093302 (2014).

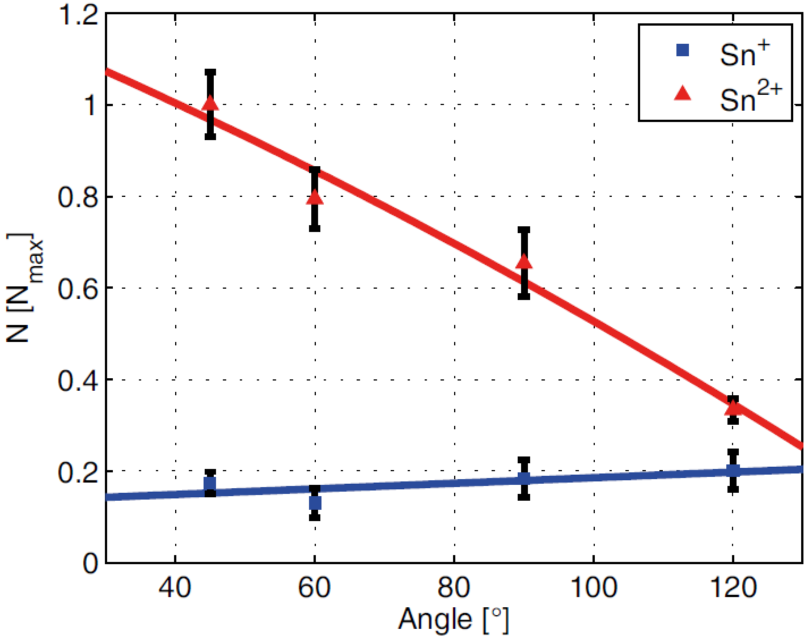
- Largest kinetic energies (damage potential) in forward direction
- Radial acceleration of ions (more pronounced on backside) at the considered length scales can be explained by self-induced electric field on the order of 30 MV/cm.

Two-dimensional ion mapping measured by ESA

- Electrostatic Analyzer (ESA) located at 150 mm from plasma at different angular positions. Different ion species can be resolved with information on abundance and kinetic energy.



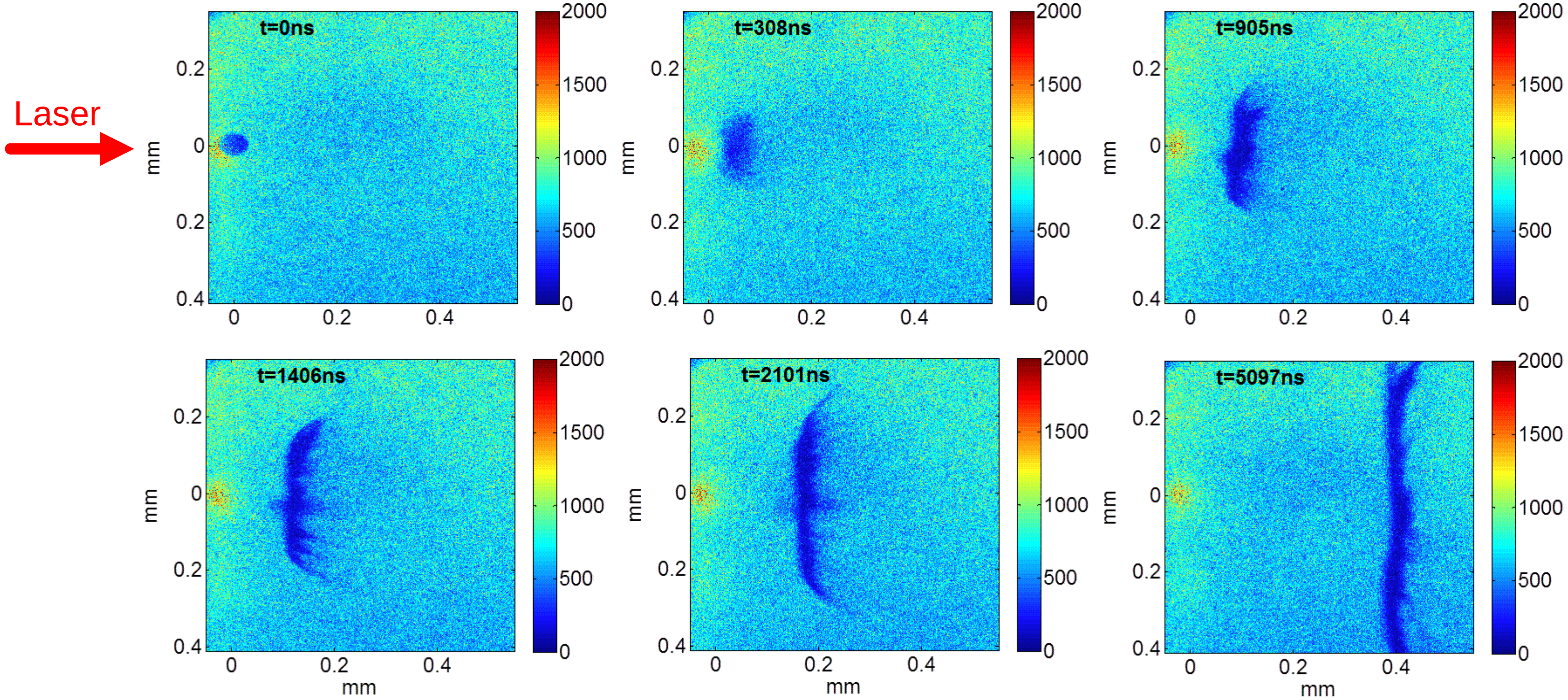
A. Z. Giovannini et. al, J. Appl. Phys. 117, 033302 (2015).



- Sn^{+} expands approximately isotropically, and Sn^{2+} expansion is anisotropic in laser forward direction (towards the incoming laser radiation).
- Results from forward peaked laser absorption region

Time-Resolved Droplet Fragment Imaging with ICCD

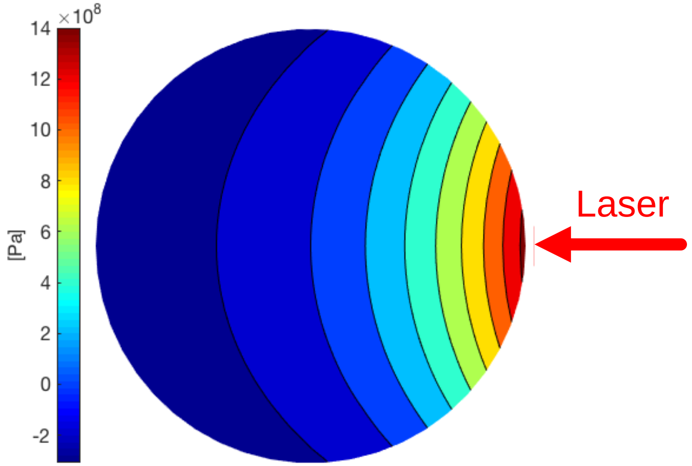
- Gated ICCD imaging with an exposure time of 250 ns
- Imaging during continuous triggered source operation at an irradiance of 150 GW/cm^2
- EUV emission is recorded for each camera exposure



Droplet Breakup Modeling

- Breakup-model consists of a spherical and a rectangular mesh containing the fragments
- The initial condition is set with a boundary integral method approximating the pressure profile on the droplet surface induced by the laser pulse
- Solving the underlying equation is done by means of a volume of fluid (VOF) model on ANSYS Fluent

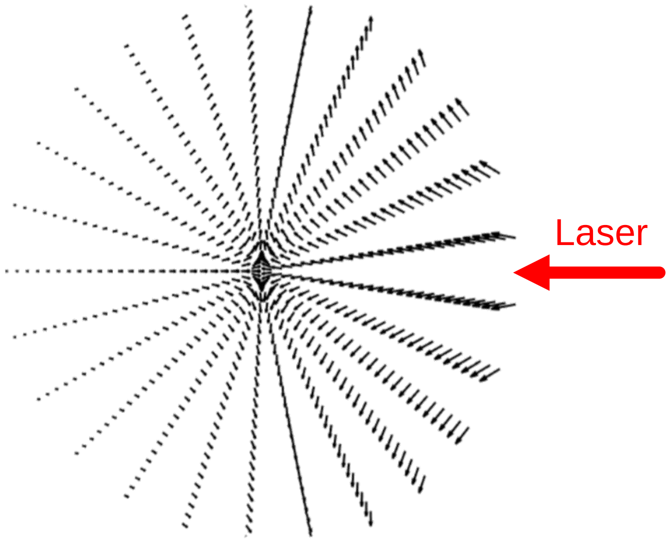
Pressure field in 2D droplet



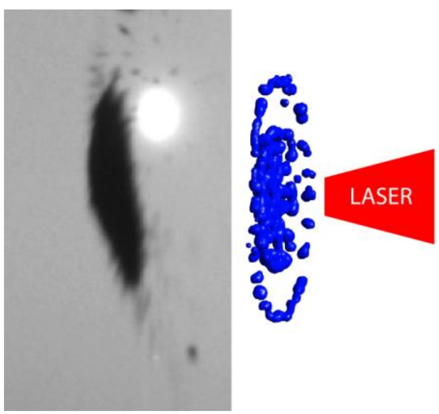
$$p(r,\Theta) = \sum_{l=0}^{\infty} A_l r^l P_l(\cos\Theta)$$

H. Gelderblom et. al, J. Fluid Mechanics (2016)

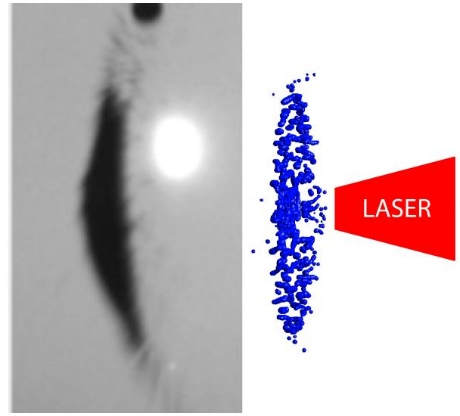
Velocity field in 2D droplet



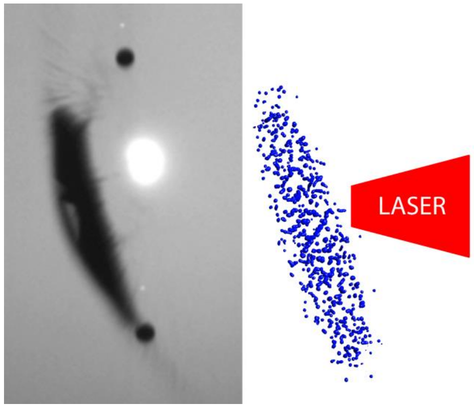
Comparison to Experimental results with Irradiance Variation



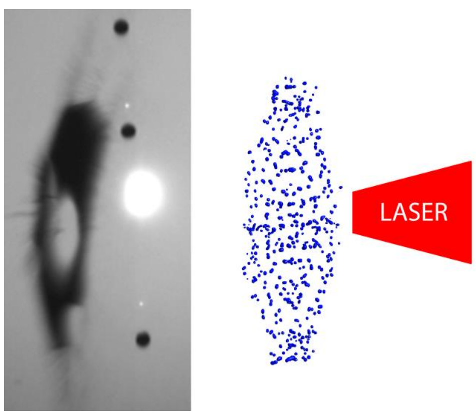
E_e = 5 GW/cm^2



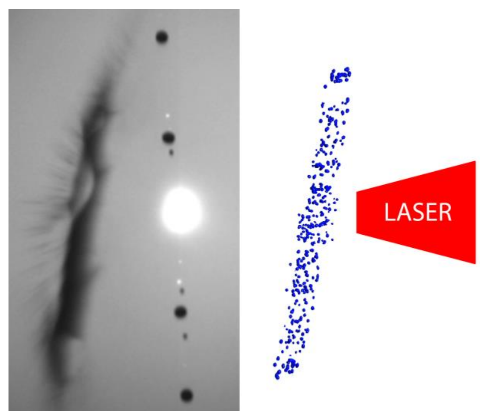
E_e = 11 GW/cm^2



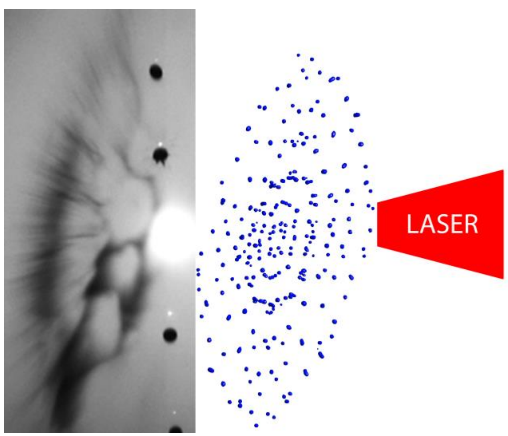
E_e = 25 GW/cm^2



E_e = 51 GW/cm^2



E_e = 85 GW/cm^2



E_e = 124 GW/cm^2

D. Hudgins et. al, J. Phys. D: Appl. Phys. (2016)

Debris Mitigation Strategy

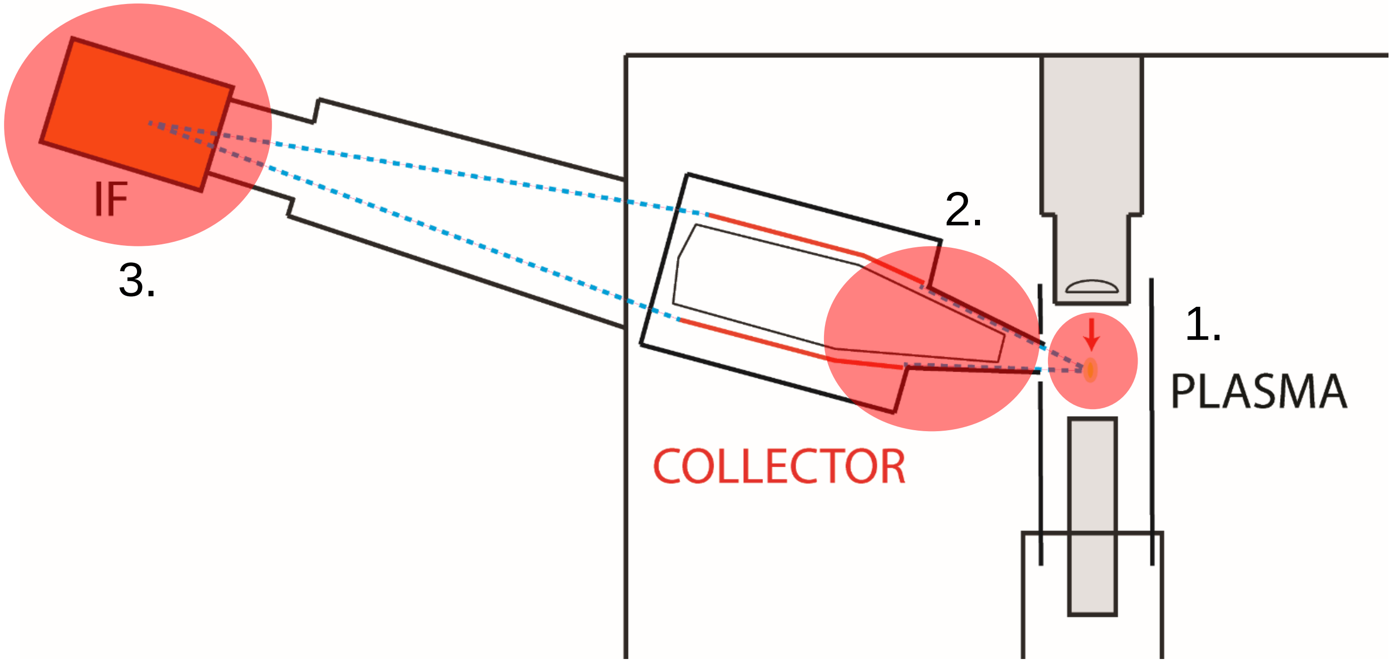
A. Limit debris formation

B. Mitigate debris

LAYER 1. Control debris around plasma

LAYER 2. Control debris in the collector module

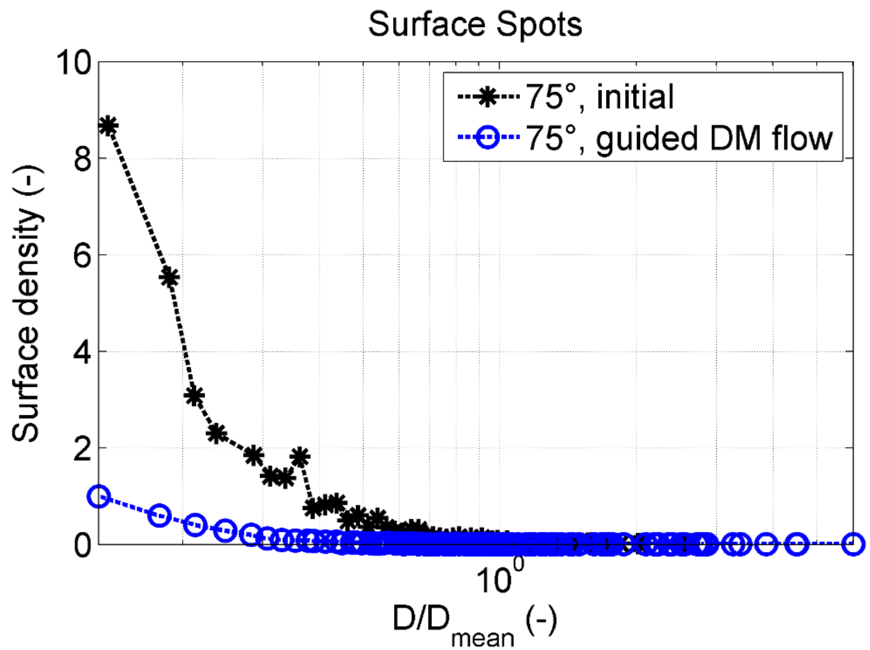
LAYER 3. Control debris at IF

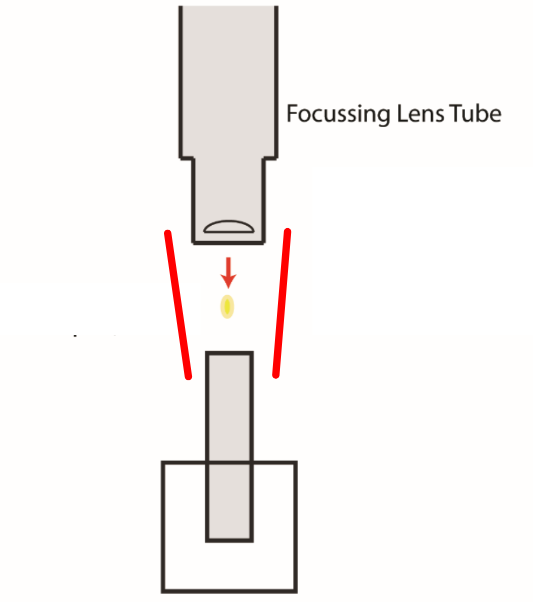


Efficient Debris Mitigation around Plasma Site

DM LAYER 1

- Optimized flow control and EUV transmission of debris mitigation gas around irradiation site
- Tin debris captured on Si witness plates



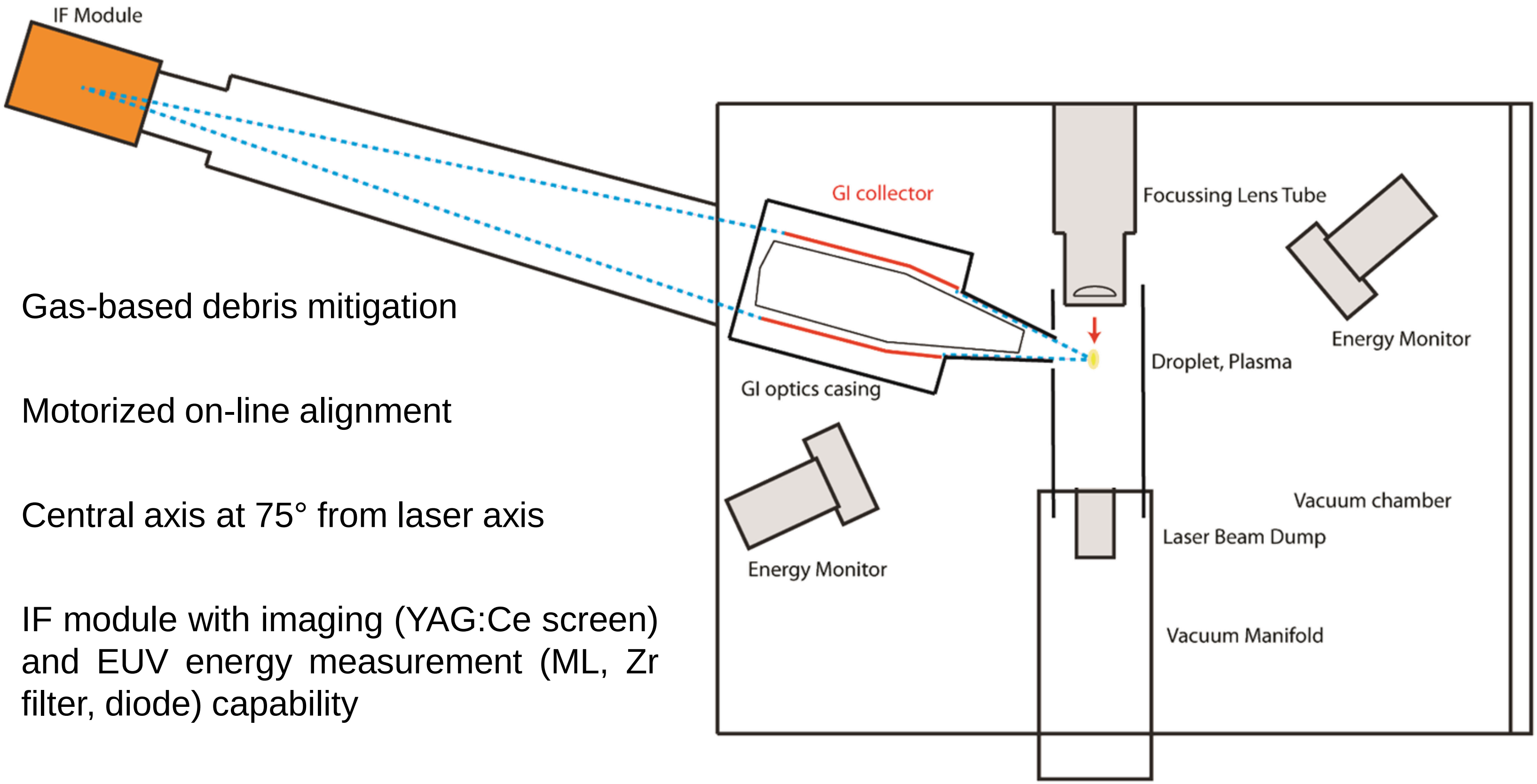


- Low energy debris is entrained by high momentum flow.
- Significant reduction (9x) of covered surface by efficiently tuning and guiding mitigation gases in the vicinity of the plasma. EUV emission is kept constant.

Source Collector Module

DM LAYER 2

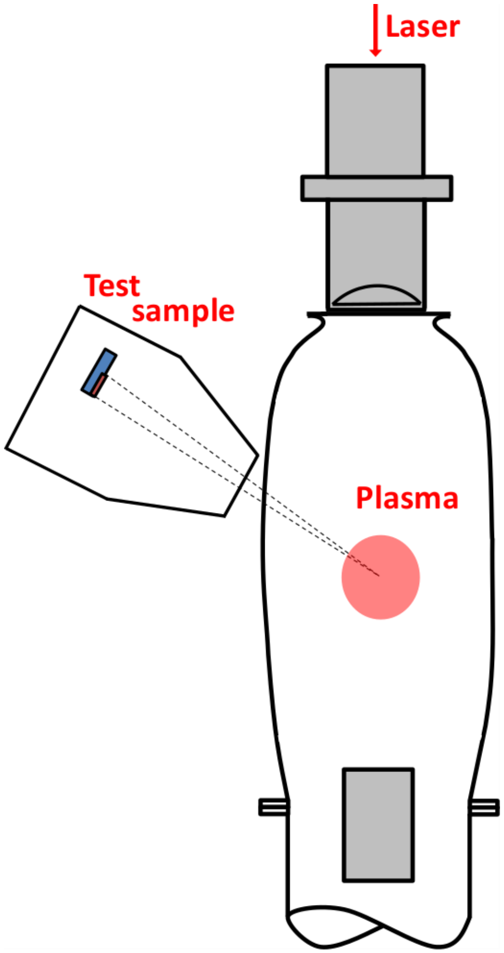
- Grazing Incidence (GI) collector for diagnostics and imaging



- Gas-based debris mitigation
- Motorized on-line alignment
- Central axis at 75° from laser axis
- IF module with imaging (YAG:Ce screen) and EUV energy measurement (ML, Zr filter, diode) capability

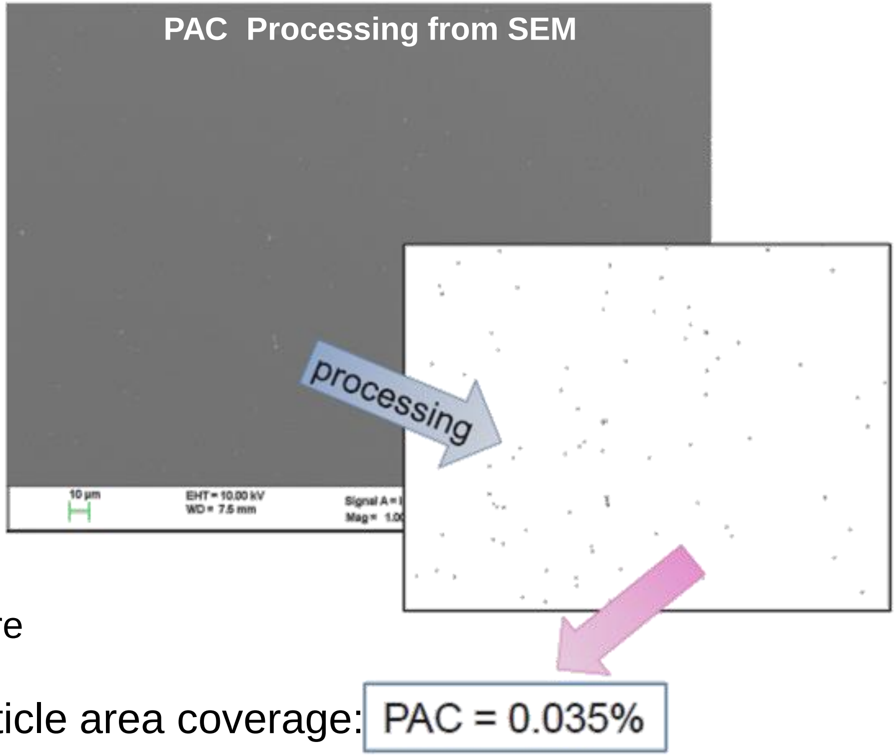
Lifetime assessment of EUV collection optics

- Measurement set-up for grazing incidence collection optics
  - **EUV source operation conditions**
    - Long term operation of 14 hours
    - 6 – 20 kHz repetition rate
    - Nominal debris mitigation settings
    - Monitoring of EUV radiation
  - **Exposure of 1” Ruthenium (Ru) samples**
    - At nominal collector distance
  - **Sample contamination was analyzed with**
    - Microscopy
    - Scanning electron microscope (SEM)
    - EUV reflectometry
    - X-ray photoelectron spectroscopy (XPS)



Results lifetime assessment of EUV collection optics

- Measurement set-up for grazing incidence collection optics
  - **Microscopy – Particle Area Coverage (PAC)**
    - At nominal collector distance:
      0.1 % after 14 hours of exposure
  - **SEM – PAC**
    - At nominal collector distance:
      PAC = 0.035 %
  - **EUV reflectometry**
    - No reflectivity loss after 14 hours of exposure
      (no changes detectable below ~1 %)
  - **XPS**
    - At nominal collector distance:
      No differences detectable after sample exposure



Particle area coverage:

- **Acknowledgment**
  - Carl Zeiss SMT for collaboration and agreement to publish

Summary and Conclusions

- Ultra High Brightness LPP EUV light source. Operates as a clean light source for actinic inspection over hundreds of hours, with validated cleanliness, stability and brightness
- Exceed power and brightness requirements for all EUV mask inspection tools (Blank, AIMS & Pattern) for foreseeable nodes.
- Fulfills stability requirements (pulse to pulse & average) for all EUV mask inspection tools
- Three layer debris mitigation strategy including plasma site, collector and IF. Grazing and normal incidence collectors integrated in source.
- Validation of source cleanliness on first bounce grazing incidence collector over long term source operation of 14 hours at maximum power with no measureable amount of debris
  → Cost of Ownership validated
- Current roadmap focusing on 24/7 operational issues.
- Design and Fabrication of ALPS III ongoing

Acknowledgments

- Swiss National Science Foundation (SNF R’Equip grant 2-77592-12)